



AUTONOMOUS OPERATIONS MISSION DEVELOPMENT SUITE

Jaime A. Toro Medina

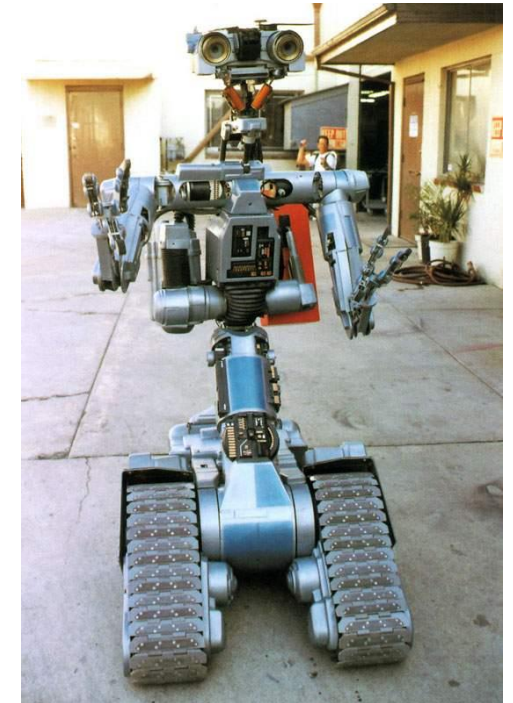
NASA Kennedy Space Center

Gensym 2016 User Forum

Orlando, FL

AGENDA

- Motivation
- ISHM-AC: Development and Applications
- AOS: Development and Application
- AO MDS
 - Development
 - Application
 - Class B Safety Critical Certification Path
- Potential Use
- Conclusions

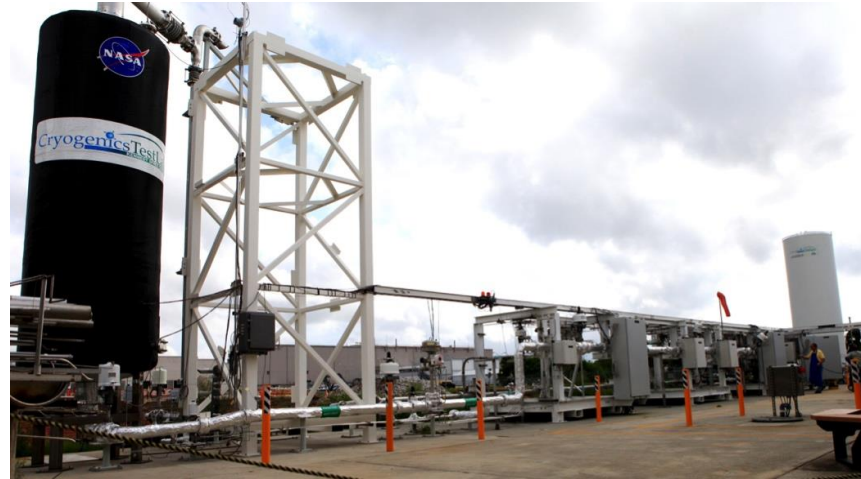


INTEGRATED SYSTEM FOR HEALTH MANAGEMENT AND AUTONOMOUS CONTROL (ISHM-AC)

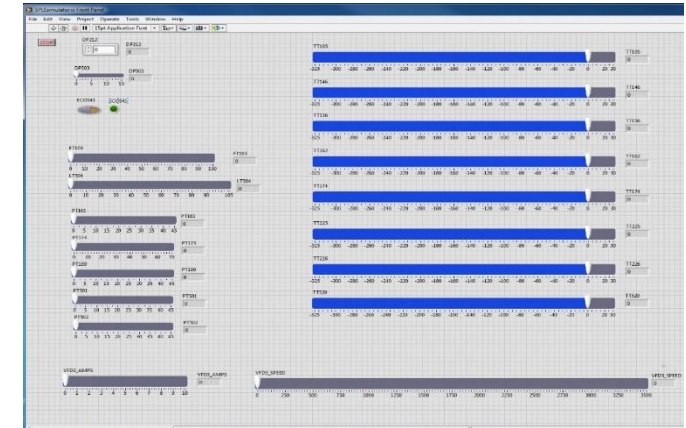


APPLICATION: 4 SIMULATED PROPELLANT LOADING SYSTEM (SPLS)

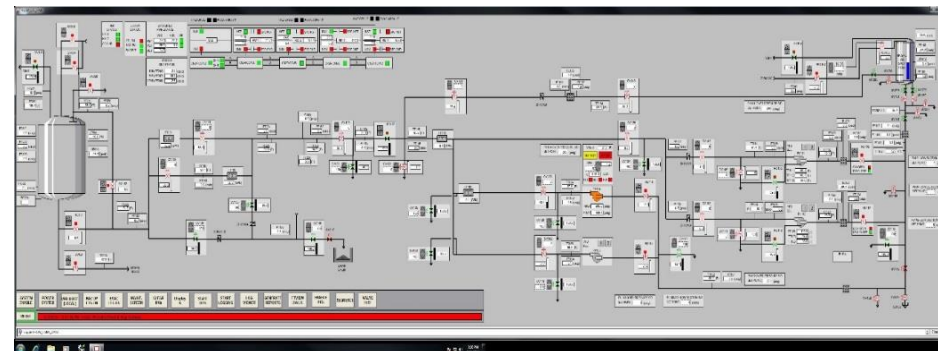
- Propellant Transfer Lines
- Storage Tank
- Simulated Vehicle
- Instrumentation
- Data Acquisition
- Command and Control System
- Simulator
- Verification and Validation
- Certified
- Technology Testing Platform



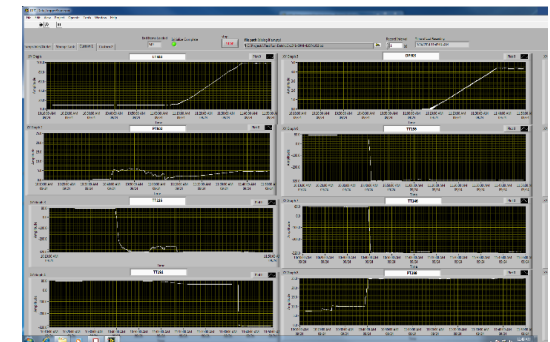
SPLS Full Configuration



SPLS Simulator



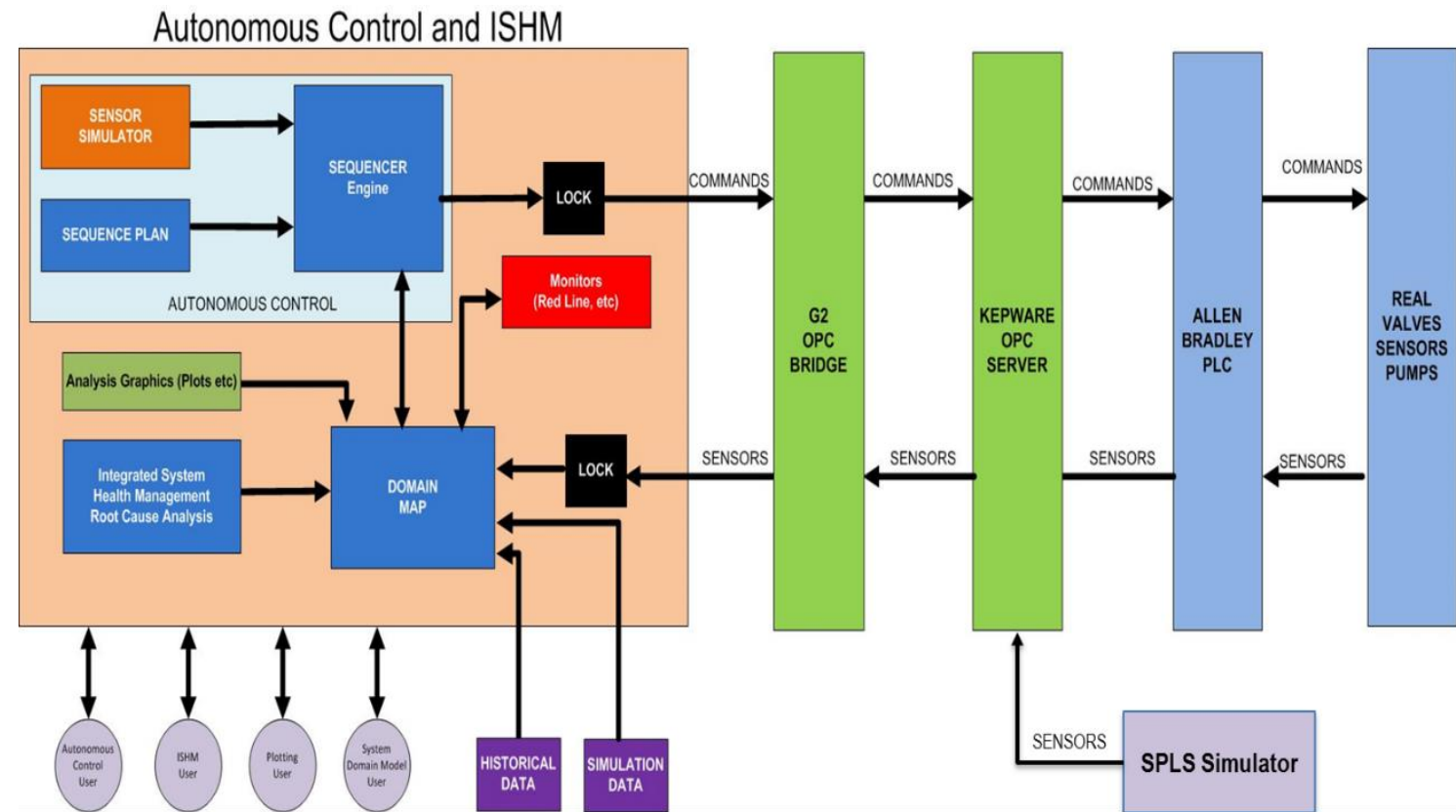
PLC DAC, Command, and Control System

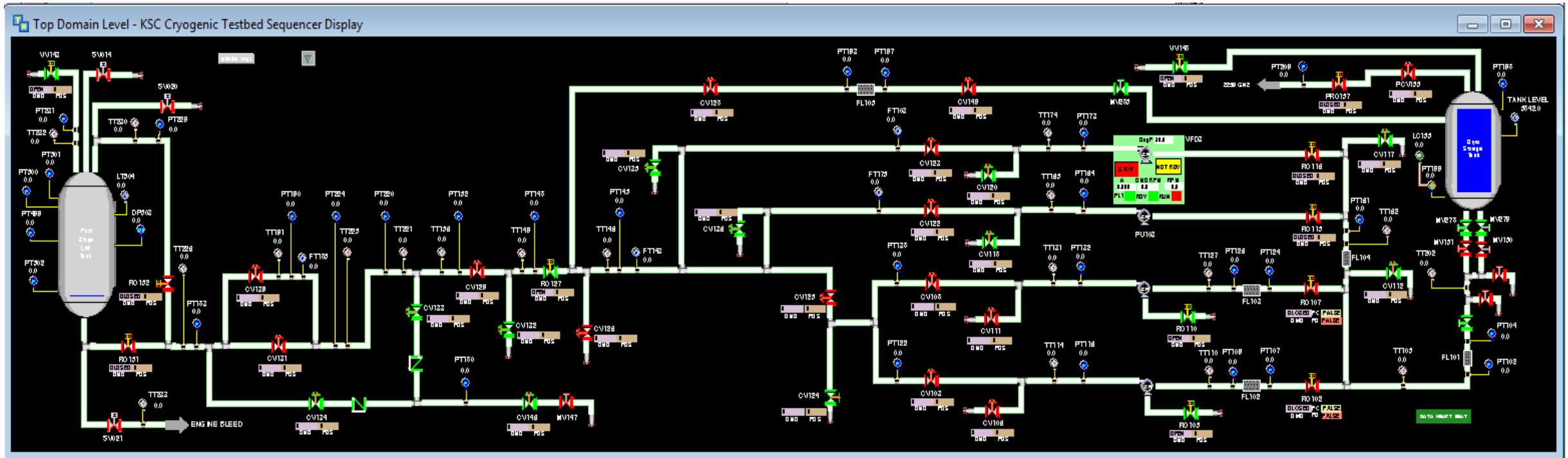


Real-time Plotting Monitoring Tool

SOFTWARE ARCHITECTURE

- Application
- Knowledge Base
- Modeling
- Automated Control
- Monitoring
- User Interface
- External I/O
- Autonomous Control
- External Simulator





APPLICATION DEVELOPMENT SYSTEM – OPERATOR USER INTERFACE

- Plan Execution
- Redline Monitoring
- Console Message
- Timers

The screenshot displays the Operator User Interface (OUI) for the Application Development System. The interface is divided into several sections:

- Top Menu Bar:** Includes Control, Mission, Console, Planning, Plotting, ISHM Map, Replay Console, Manual Valves, OPC-SPP Bridge, Diagnosis, and Domain Maps.
- ALL Monitors - Click STATUS to manually ACTIVATE/DEACTIVATE - Click PLAN to SELECT PLAN or set to NO PLAN:** A table showing the status of various monitors.

Monitor	Status	State	Alternate	Trigger Plan	Triggered	Lower Active	Lower Limit	Higher Active	Higher Limit	Activation Plan
MAV-4-02-COMMAND-FAIL...	Deactivate	HEALTHY	UNAVAILABLE	No Plan	Not Triggered	No	0.0	Yes	0.5	Not Activated
PT-10-02	Deactivate	HEALTHY	UNAVAILABLE	APL Advance to Shutdown_v2	Not Triggered	Yes	40.0	No	0.0	Not Activated
SV-1-02-FAIL-CLOSE	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown_v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-4-02-STUCK-OPEN	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown_v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-3-02-STUCK-OPEN	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown_v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-2-02-STUCK-OPEN	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown_v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-1003-02-FAIL-CLOSE	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown_v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-1002-02-FAIL-CLOSE	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown_v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
- SEQUENCE PLAN CONTROL - Nominal Sequence v1 - Chidown & Loading & Replenish - Mod f...**
 - STEPS EXECUTED:** A table showing the progress of the sequence.

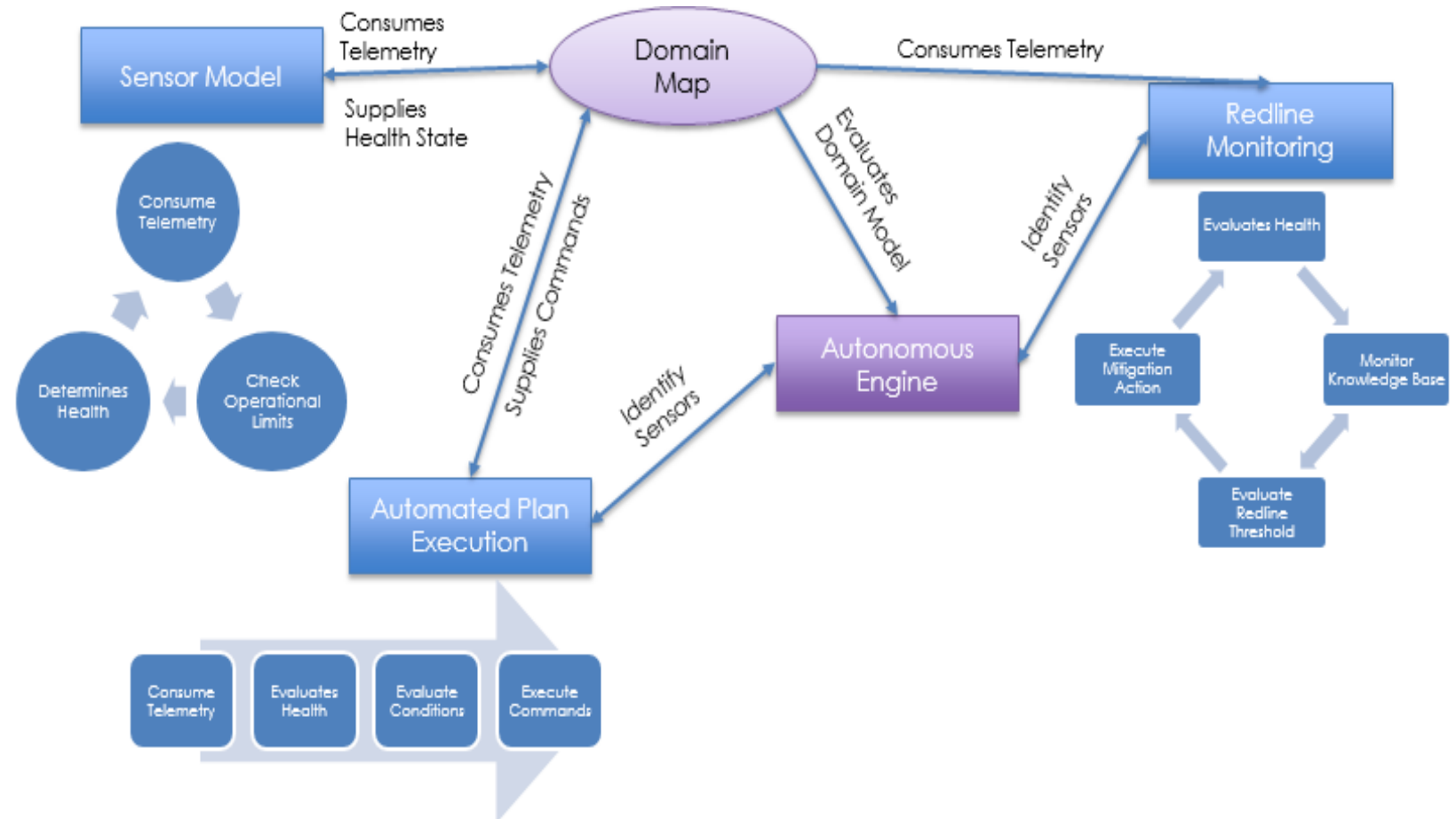
Step Label	Trigger	Boolean	Condition
Step-1-1			
Step-1-1	MAV-1001-02-FAIL-CLOSE-L...		
Step-1-1	MAV-1002-02-FAIL-CLOSE-L...		
Step-1-1	MAV-1003-02-FAIL-CLOSE-L...		
Step-1-1	MAV-2-02-STUCK-OPEN-L-0...		
Step-1-1	MAV-3-02-STUCK-OPEN-L-0...		
Step-1-1	MAV-4-02-STUCK-OPEN-L-0...		
Step-1-1	SV-1-02-FAIL-CLOSE-L-0-H...		
 - STATUS: RESET PHASE:** Buttons for START, RESET, PAUSE, RESUME, FORCE STEP ADVANCE, and SENSOR HEALTH CHECK.
 - ACTIVE STEP:** A table showing the current step and its status.

Step Label	Trigger	Boolean	Condition	Timer	Valve	Set Point	CAM View
Step-1-1				0.0			
Step-1-1	MAV-1001-02-FAIL-CLOSE-L...					ACTIVATED	
Step-1-1	MAV-1002-02-FAIL-CLOSE-L...					ACTIVATED	
Step-1-1	MAV-1003-02-FAIL-CLOSE-L...					ACTIVATED	
Step-1-1	MAV-2-02-STUCK-OPEN-L-0...					ACTIVATED	
Step-1-1	MAV-3-02-STUCK-OPEN-L-0...					ACTIVATED	
Step-1-1	MAV-4-02-STUCK-OPEN-L-0...					ACTIVATED	
Step-1-1	SV-1-02-FAIL-CLOSE-L-0-H...					ACTIVATED	
 - FUTURE STEPS:** A table showing the upcoming steps.

Step Label	Trigger	Boolean	Condition	Timer	Valve	Set Point	CAM View
Step-1-2				10.0			
Step-1-2					MAV-11-02	1.0	
Step-1-2					MAV-10-02	1.0	
Step-1-2					MAV-12-02	1.0	
Step-1-3	60.0			0.0			
Step-1-3	TT-1-02	Less Than	32.26				
Step-1-3					MAV-1-02	1.0	
Step-1-3					MAV-9-02	0.0	
Step-1-4	0.0			0.0			
- Console:** A window for displaying messages. It includes tabs for Options, Delete Msgs, Active, and Log. The Active tab is currently selected, showing a list of messages.
- Timer Control and Status for Plan Nominal Sequence v1 - Chidown & Loading & Replenish - Mod f...**
 - Timer-1 INACTIVE: LLT-1-TK-1-CH, Greater Than, 0
 - Timer-2 INACTIVE: EMPTY, Greater Than, 0
 - Timer-3 INACTIVE: EMPTY, Greater Than, 0
 - Timer-4 INACTIVE: EMPTY, Greater Than, 0
 - Timer-5 INACTIVE: EMPTY, Greater Than, 0
 - Timer-6 INACTIVE: EMPTY, Greater Than, 0
 - Timer-7 INACTIVE: EMPTY, Greater Than, 0
 - Timer-8 INACTIVE: EMPTY, Greater Than, 0
 - Timer-9 INACTIVE: EMPTY, Greater Than, 0

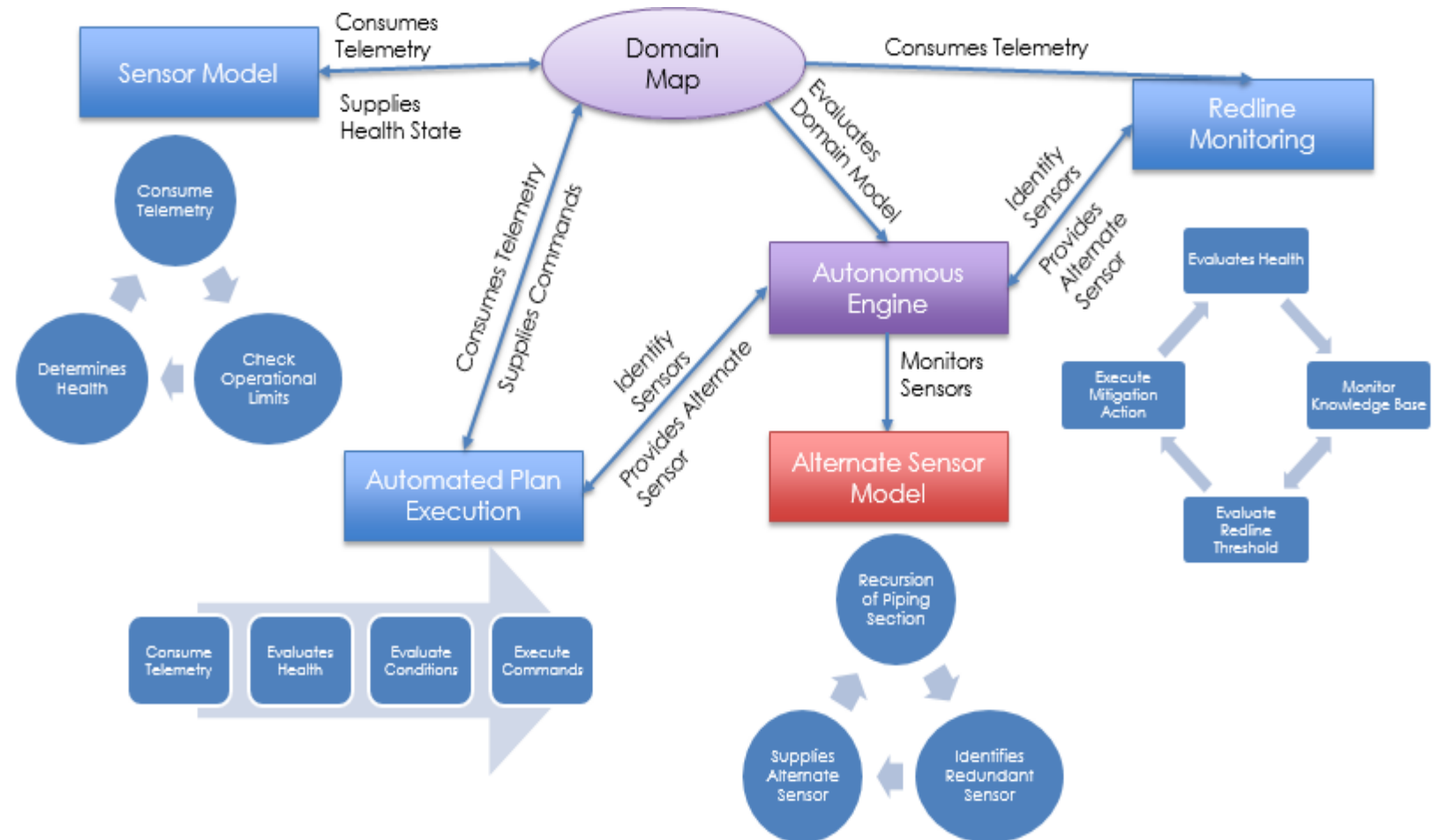
AUTONOMOUS OPERATIONS - NOMINAL

- Nominal scripted plan executed
- Redline monitoring evaluation
- Sensor Model Determining Health
- Domain Map contains application knowledge
- Autonomous Engine identifying sensors



AUTONOMOUS – OFF-NOMINAL

- Autonomous Engine
 - Executes mitigation actions
- Nominal scripted plan executed = Mitigated or Aborted
- Redline monitoring evaluation = Mitigated or Aborted
- Sensor Model Determining Health

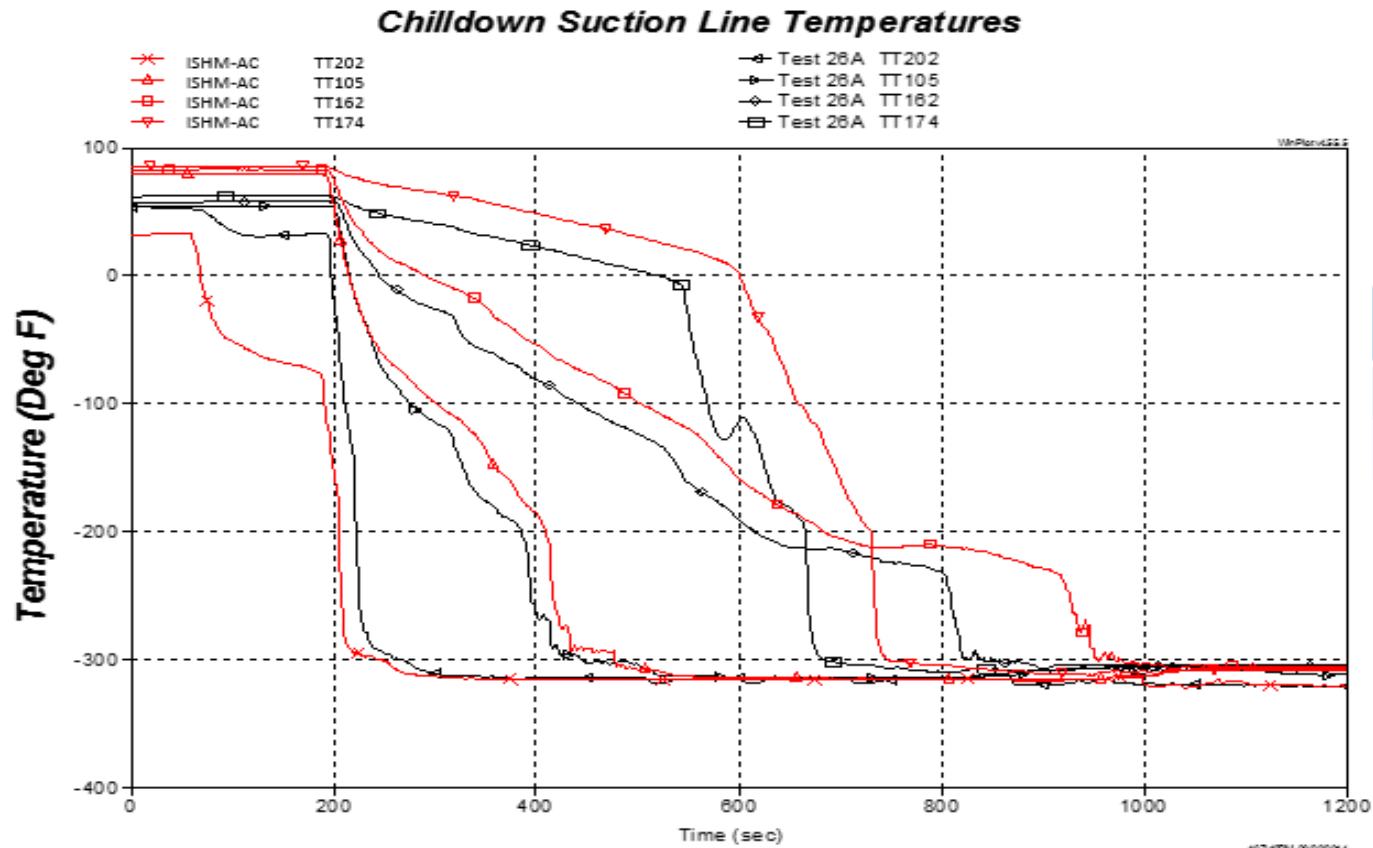


TEST RESULTS

ISHM – AC vs. SPLS Baseline



NOMINAL: CHILLDOWN PHASE – SIMULATED GSE



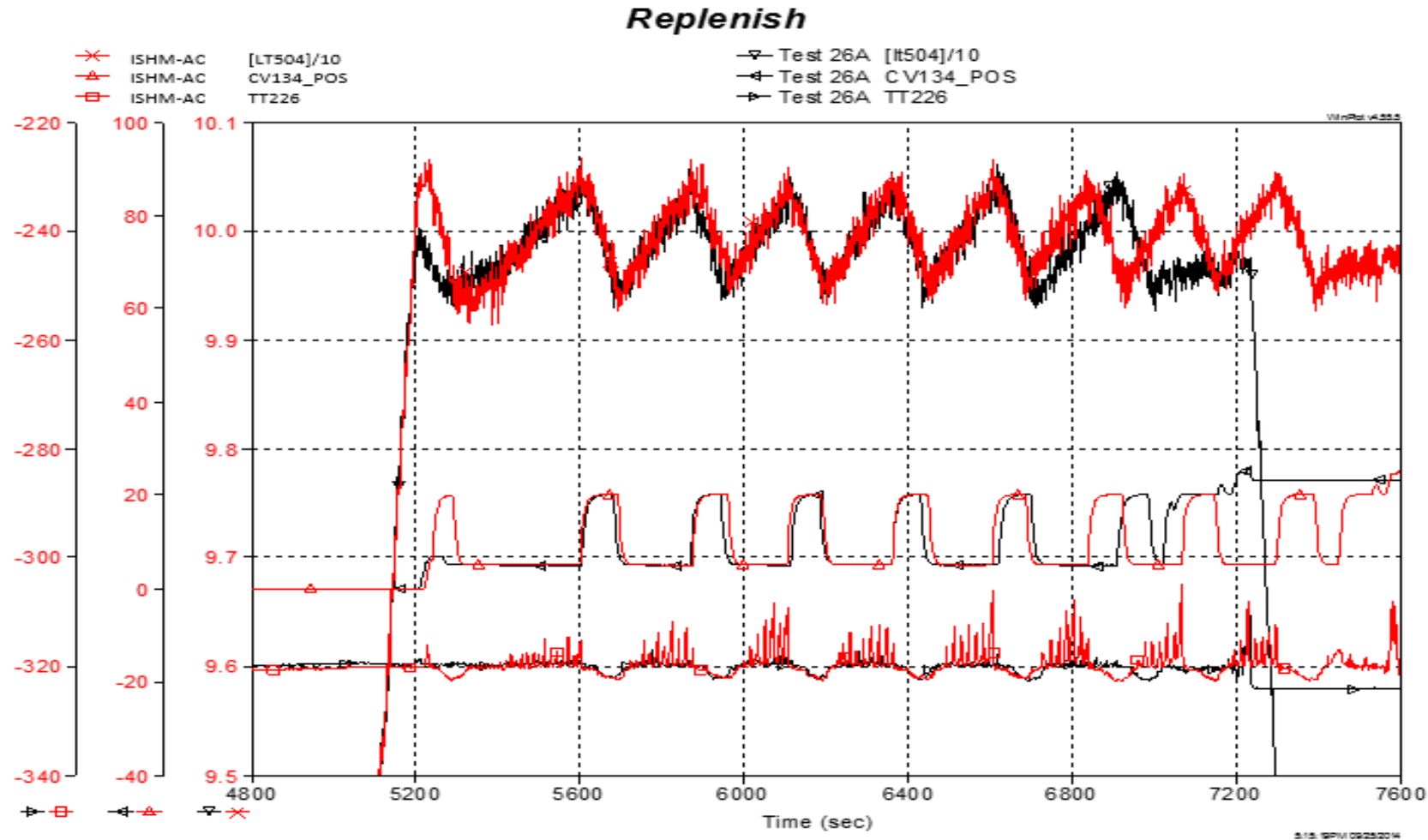
TT105: Tank-Pump Suction

TT202: Tank Discharge

TT162: Pump Suction

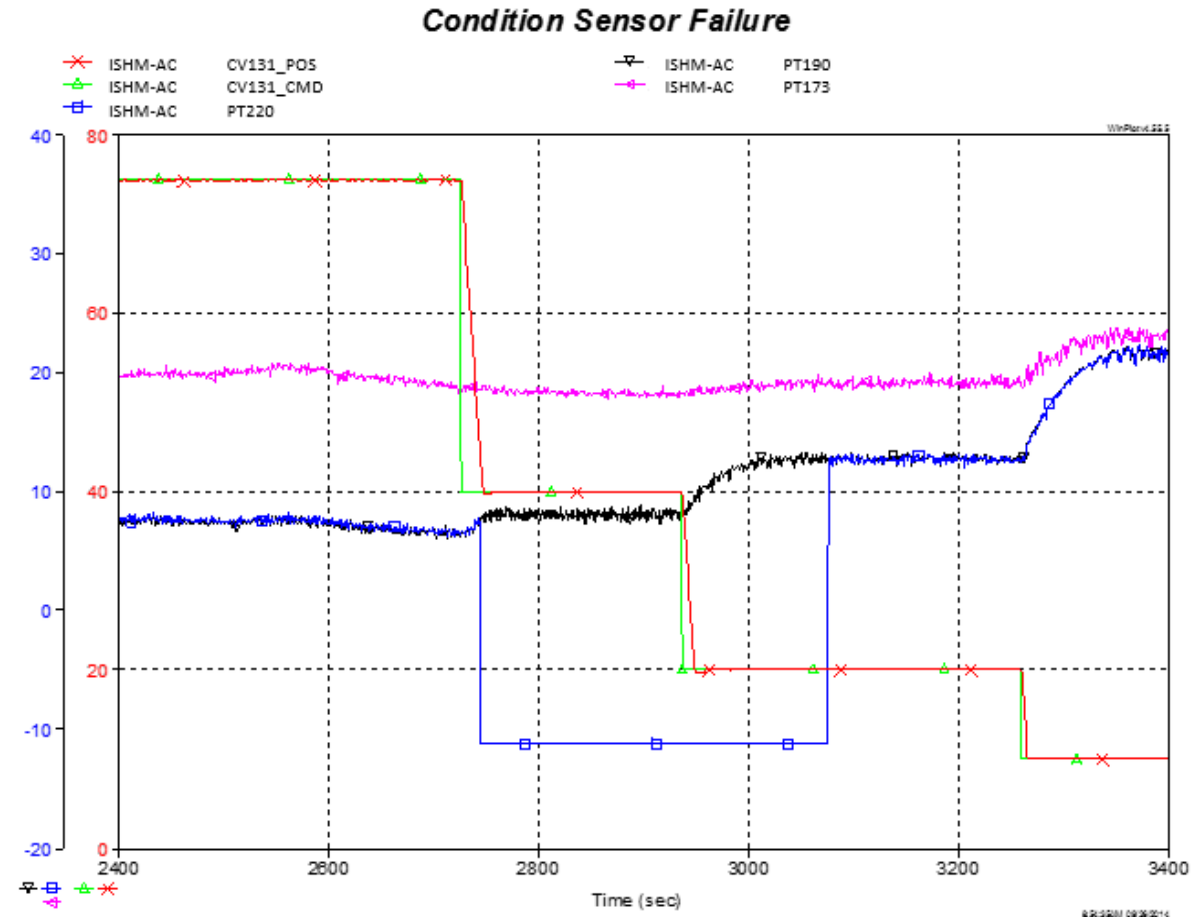
TT174: Pump Discharge

NOMINAL: REPLENISH PHASE – SIMULATED FLIGHT VEHICLE



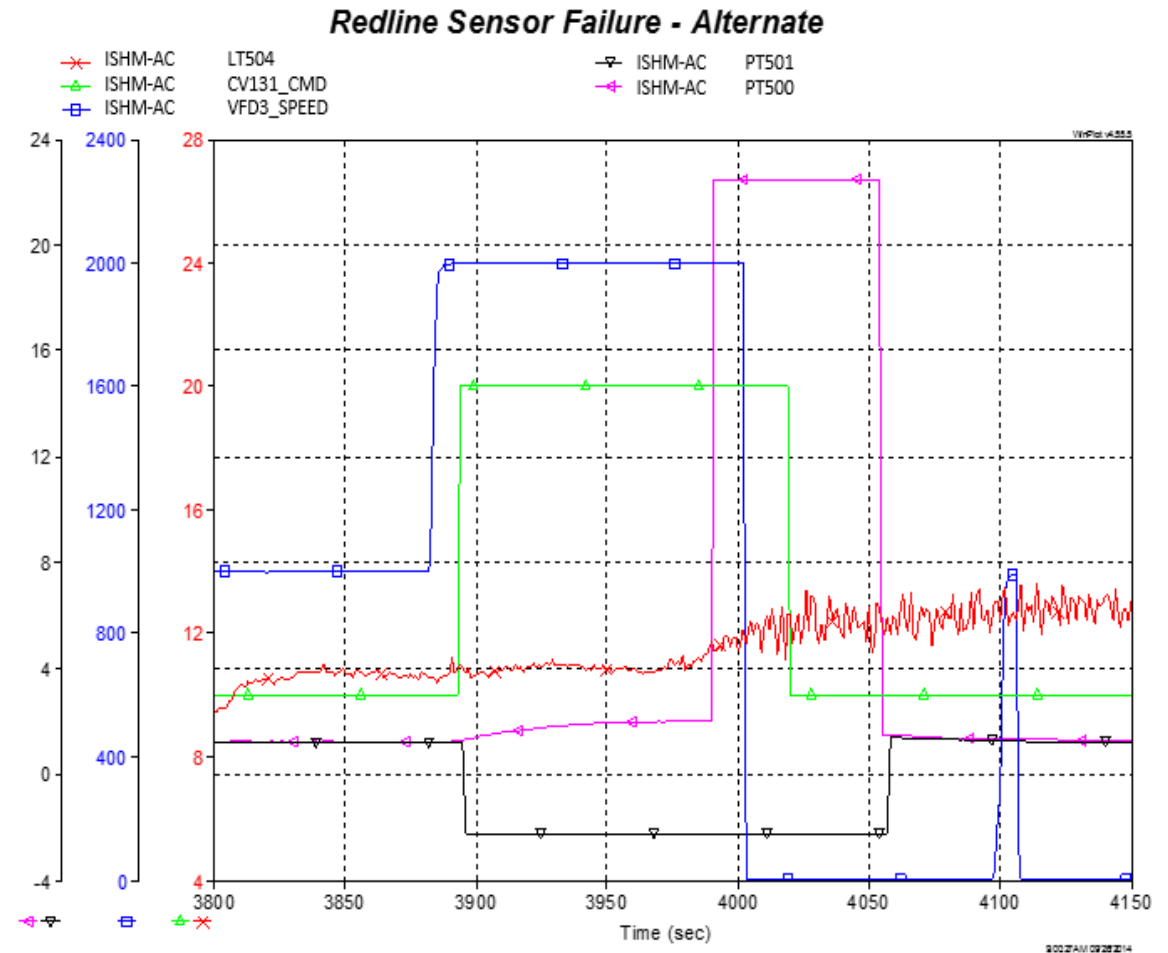
OFF-NOMINAL: AUTONOMOUS ENGINE

- Plan Execution
- Failure Insertion
- Alternate Sensor Model
- Mitigation Telemetry
- Plan Execution Continuation



OFF-NOMINAL: AUTONOMOUS ENGINE

- Redline Monitoring
- Failure Insertion
- Alternate Sensor Model
- Mitigation Telemetry
- Redline Monitoring Continues



CONCLUSION

- ISHM-AC: Verification and Validation of Autonomous Operations
- Application supports real-time laboratory operations with cryogenic commodity
- Support mitigation procedures that allows safe continuation of operations
- NASA Technology Readiness Level (TRL) from an analytical and experimental proof-of-concept (Level 3) to validation in laboratory environments (Level 4)



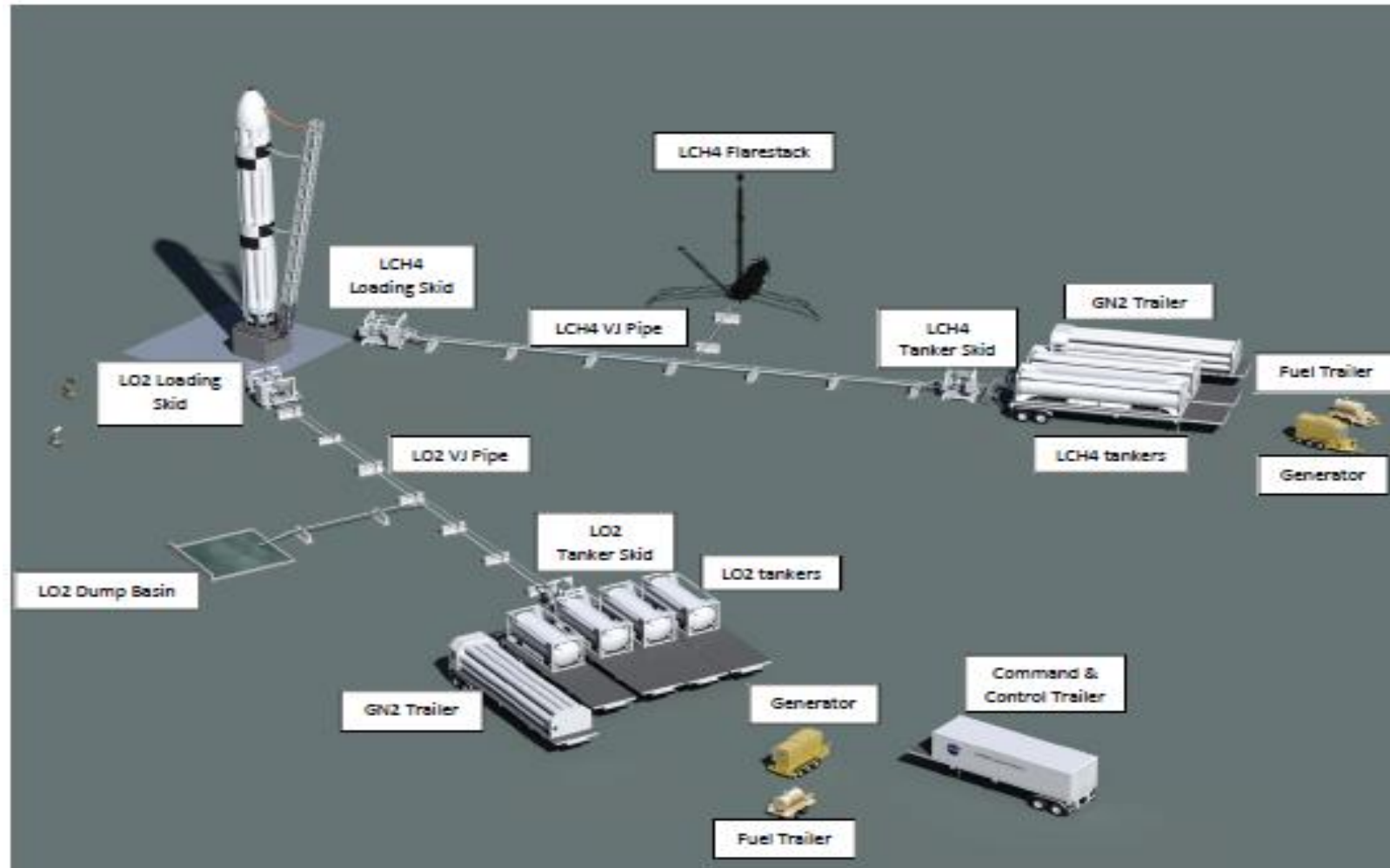
WHAT'S NEXT?

- Increase to higher TRL 4 → 5
- Use the software in Ground Support Equipment (GSE)
- Real cryogenic propellant
- Expand capabilities
- Improve models
- Failure scenarios similar to real GSE.
- GSE Space Shuttle similar failure cases
- Support more complex concept of operations.

AUTONOMOUS OPERATIONS SYSTEM (AOS)

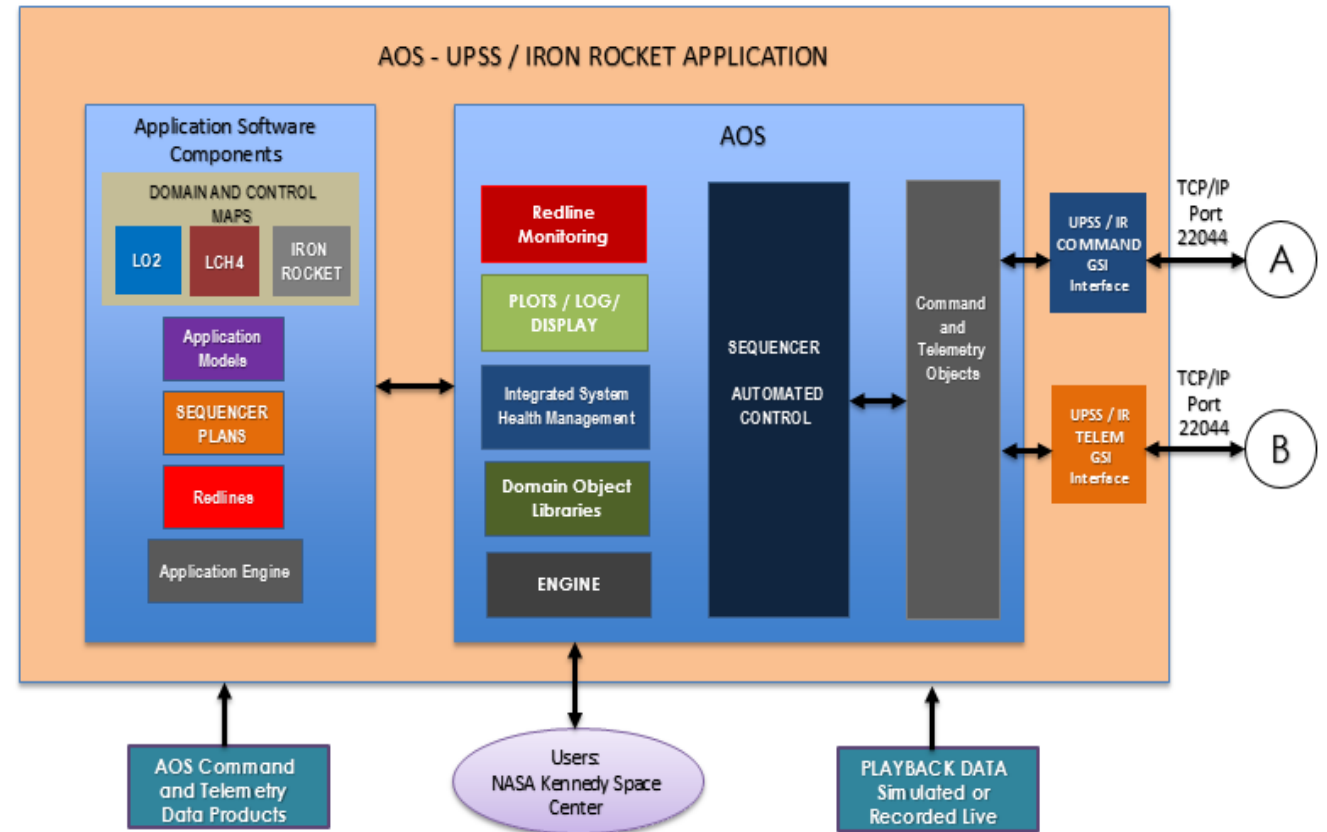


APPLICATION – UPSS AND IRON ROCKET



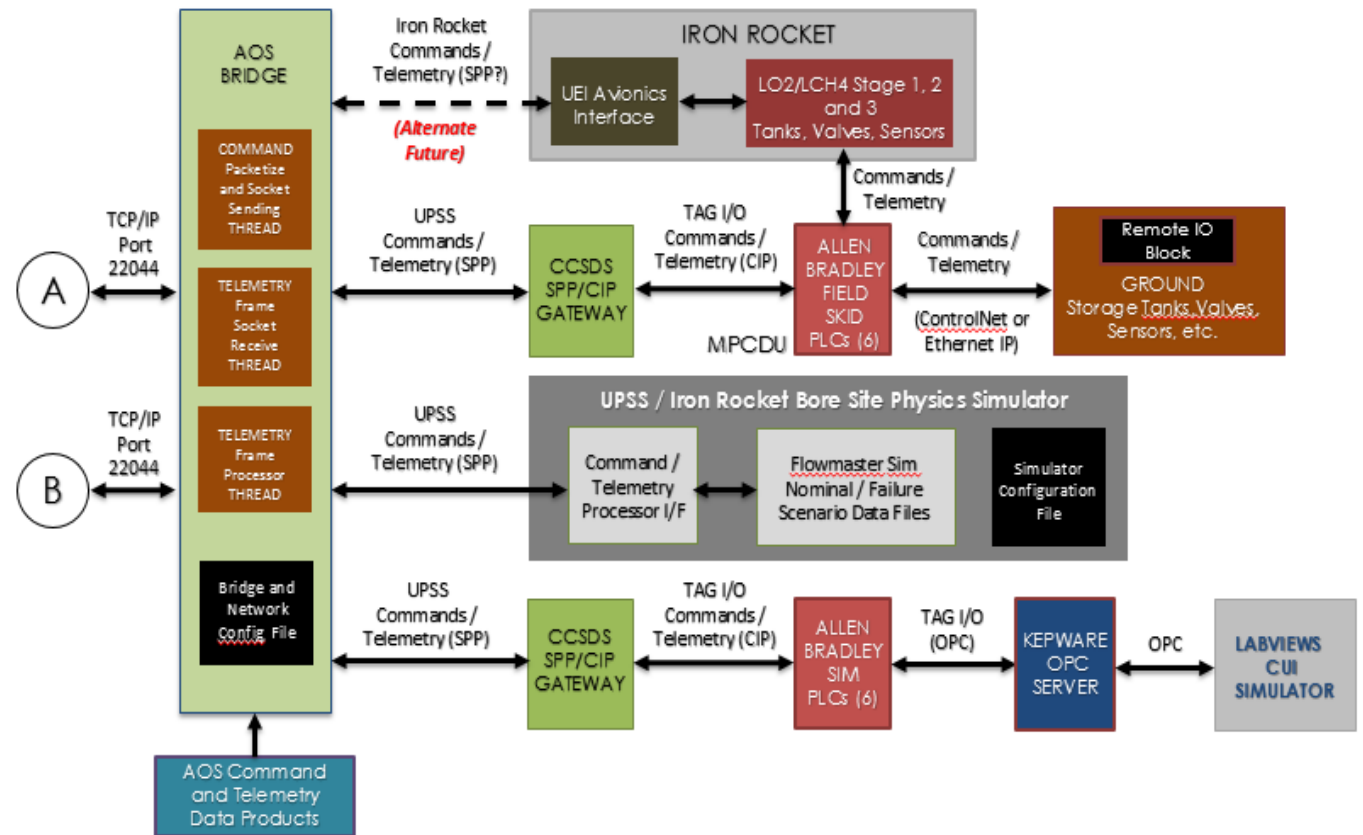
SOFTWARE ARCHITECTURE

- ISHM-AC
- AOS
 - Different Communication Protocols
 - New Bridge and Gateway
 - Expanded Application Layer
 - Standardized Database
 - Modular Domain and Displays
 - Application engine and generic engine
 - Library expansion

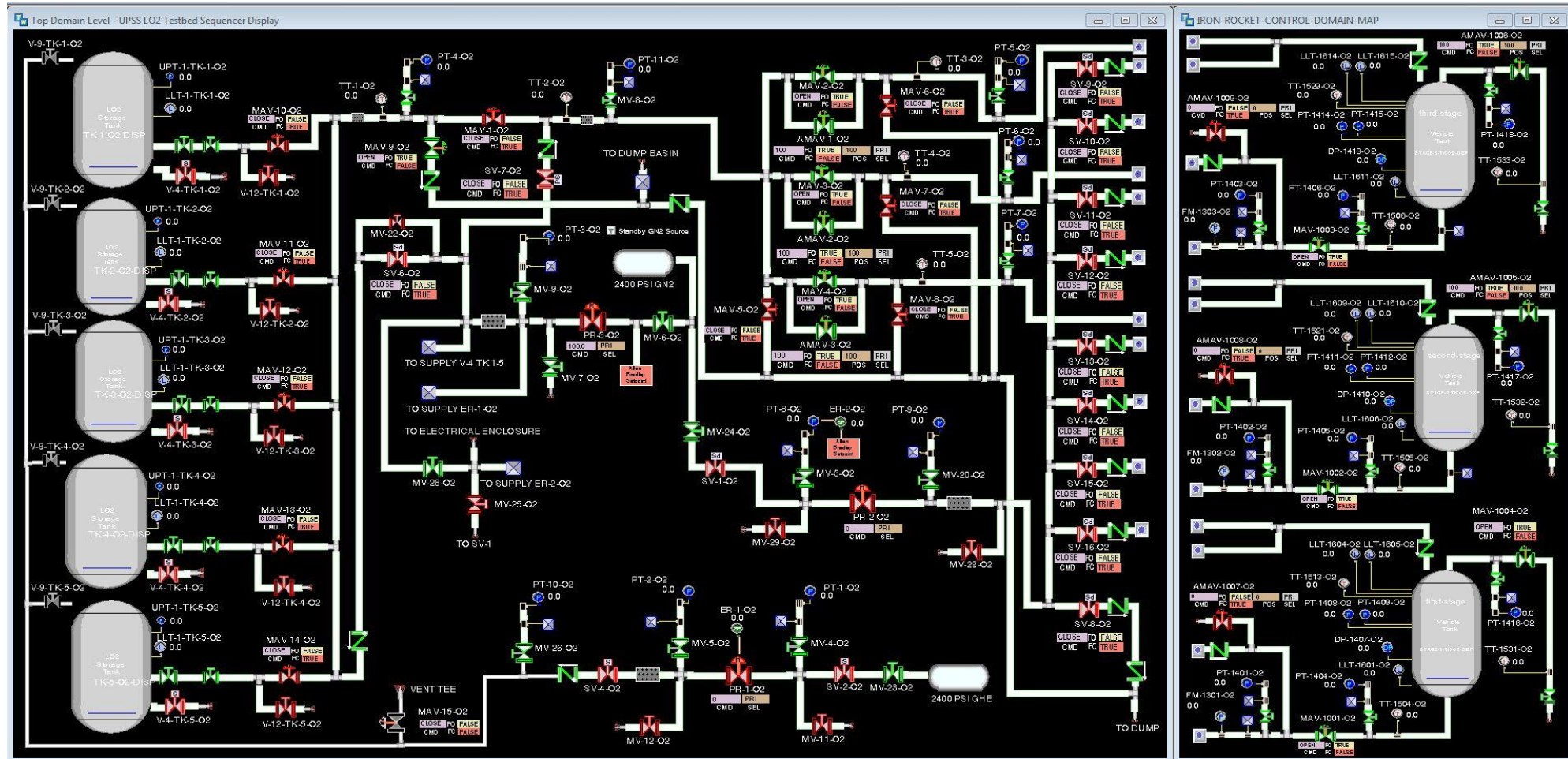


SOFTWARE ARCHITECTURE – CONT.

- AOS
 - Redundancy modifications and modeling
 - Physics Model and Simulator
 - Multi-source telemetry support
 - Several PLC interactions



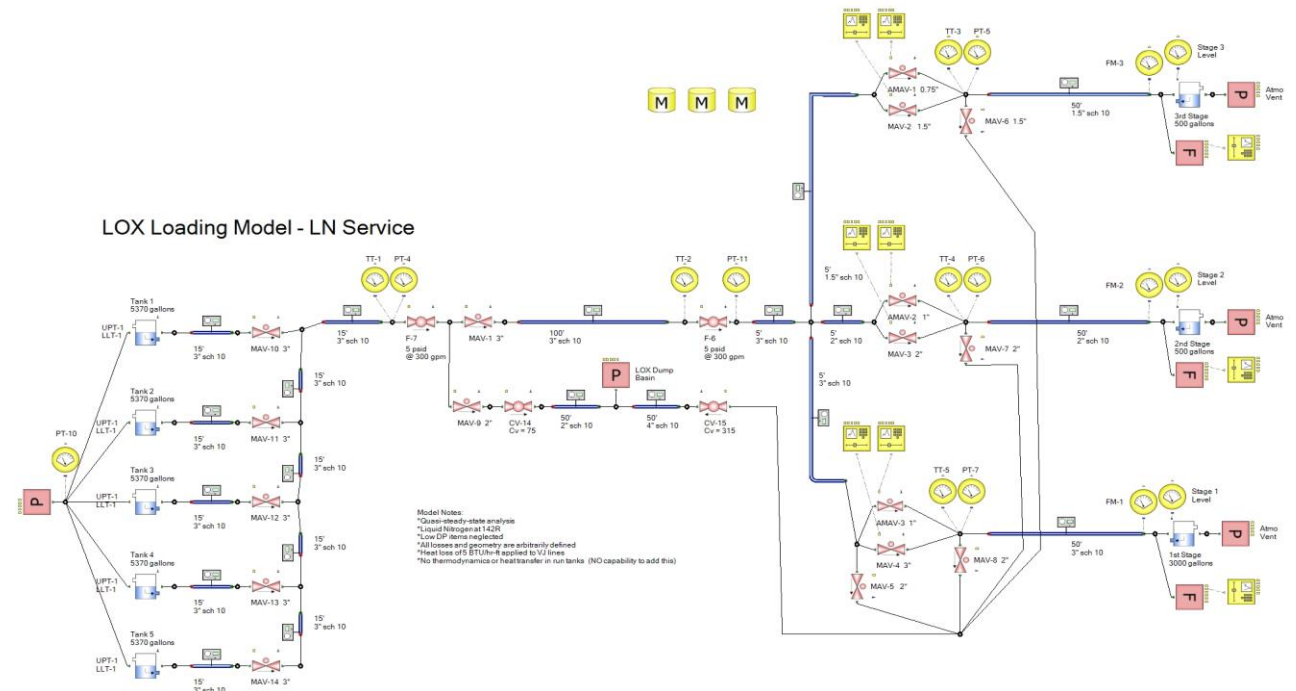
UPSS AND IRON ROCKET CONTROL MAPS



PHYSICS MODEL



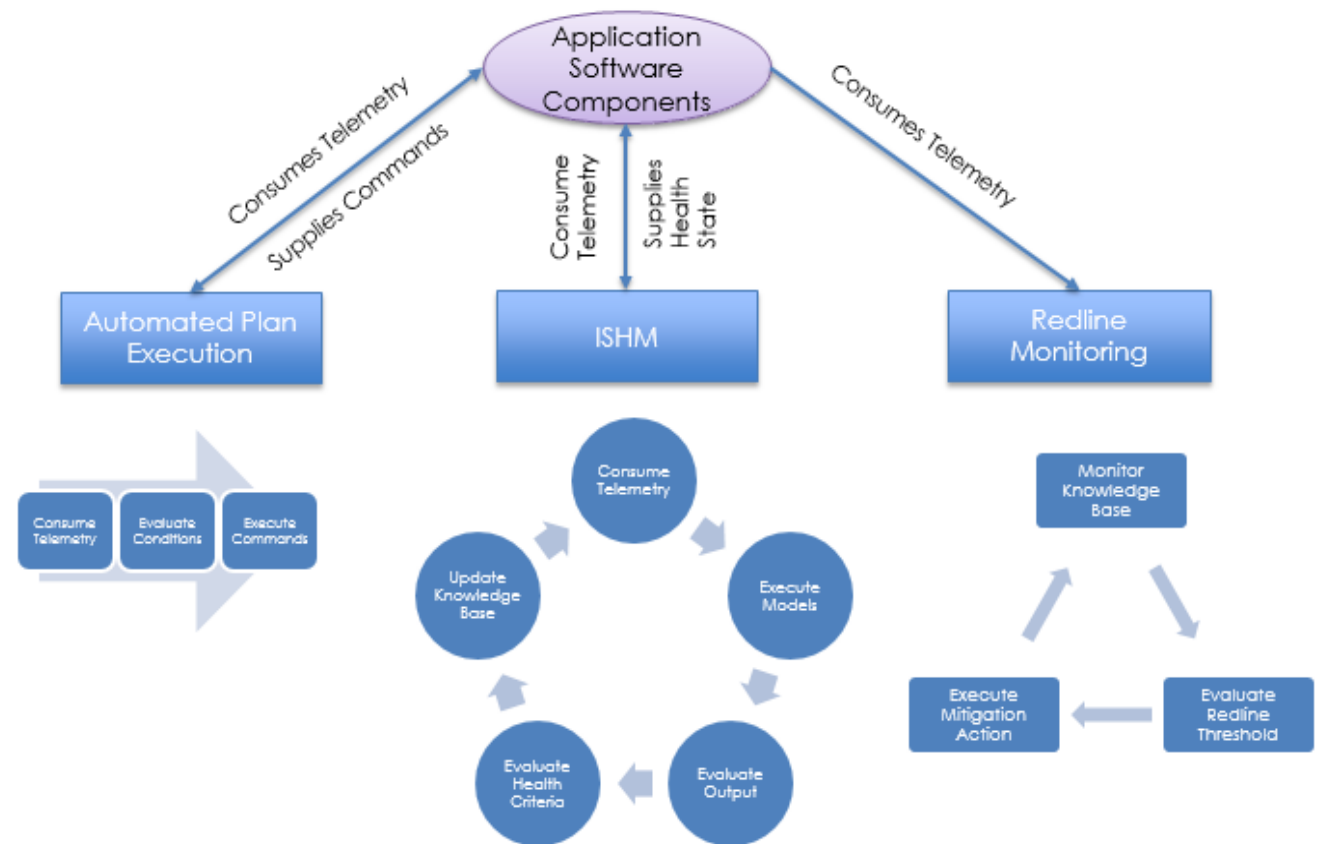
DTS Vehicle Simulator



UPSS and DTS Physics Model

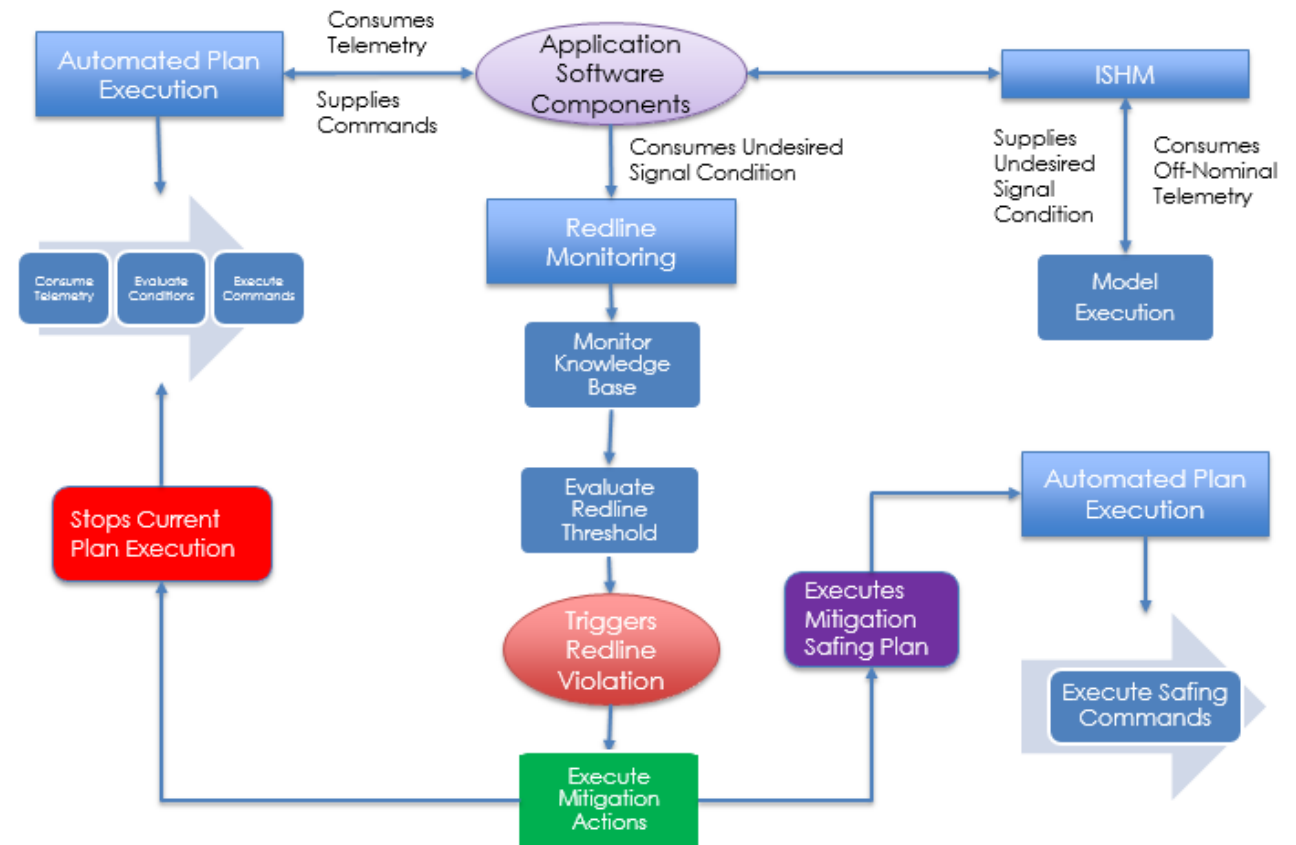
AUTONOMOUS OPERATIONS - NOMINAL

- Application Software Components
 - Telemetry/Command
 - Domain Model
 - Data Processing
- Nominal scripted plan executed
- Redline monitoring evaluation
- ISHM executes models and evaluates health



AUTONOMOUS – OFF-NOMINAL

- Models Determines Off-Nominal Conditions
- Redline monitoring executes mitigation actions
- Nominal plan execution is aborted
- Safing plan executes



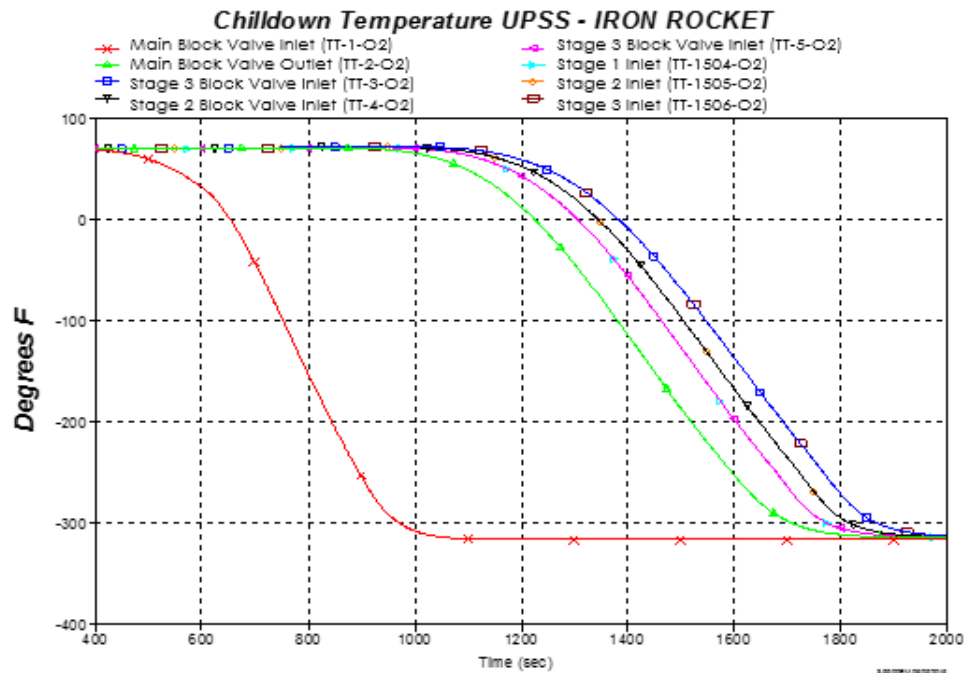
TEST RESULTS

AOS on UPSS and DTS

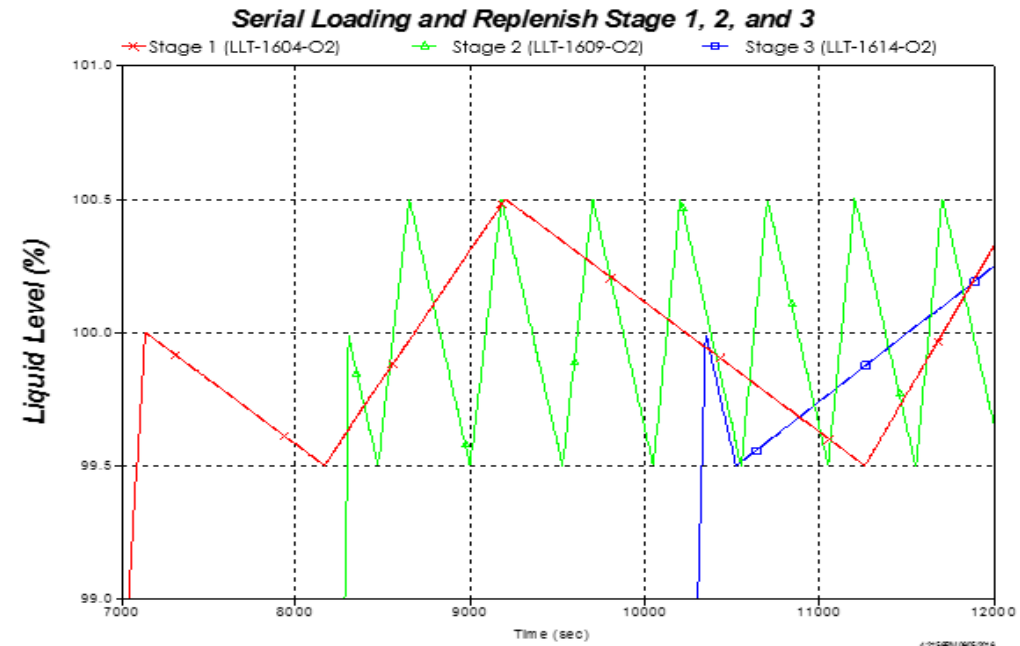


NOMINAL OPERATIONS

- Chillydown operations
 - UPSS Chillydown
 - Main Inlet Block Valve
 - Simulated Vehicle Inlet
 - Parallel chillydown operation



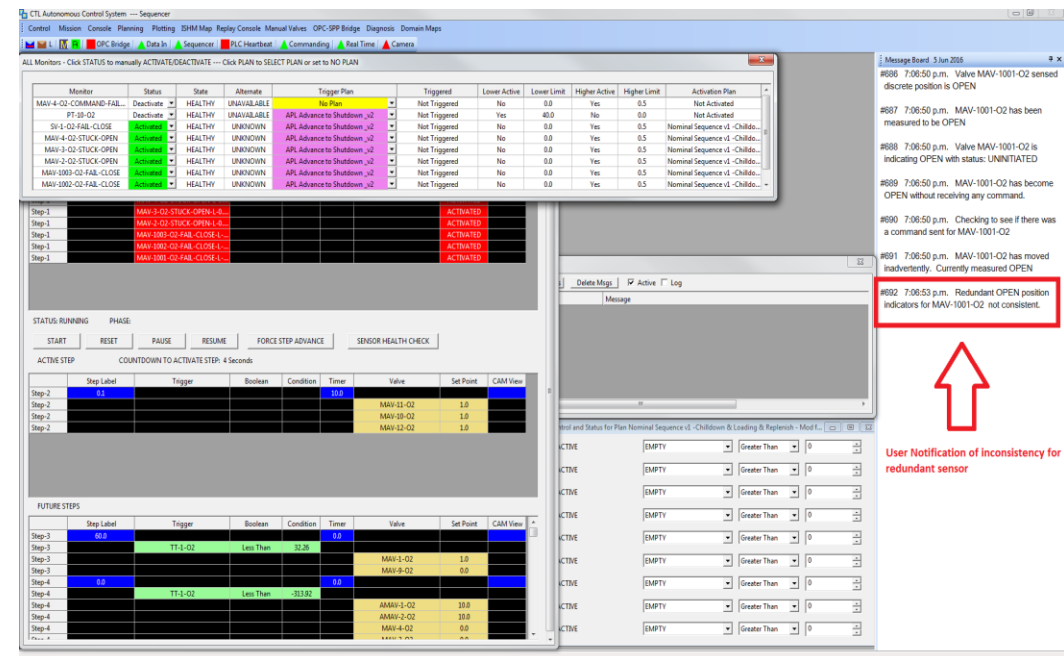
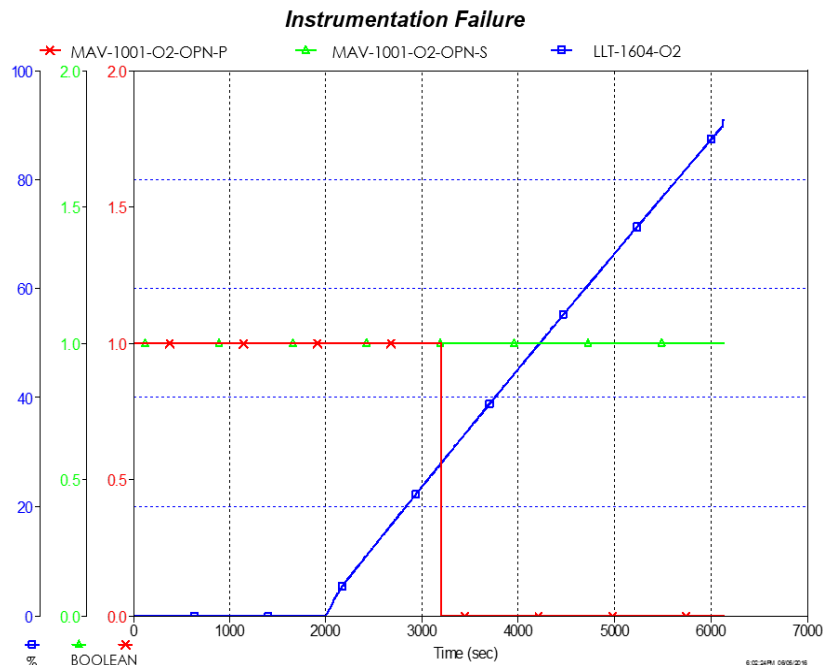
- Serial Loading
 - Slow-Fast Fill Stage 1
 - Replenish Stage 1
 - Load Stage 2
 - Continue with Stage 3



OFF-NOMINAL OPERATIONS

- Non-Safety Critical
 - Stage 1 inlet valve primary position indication failure
 - Secondary sensor continues operations

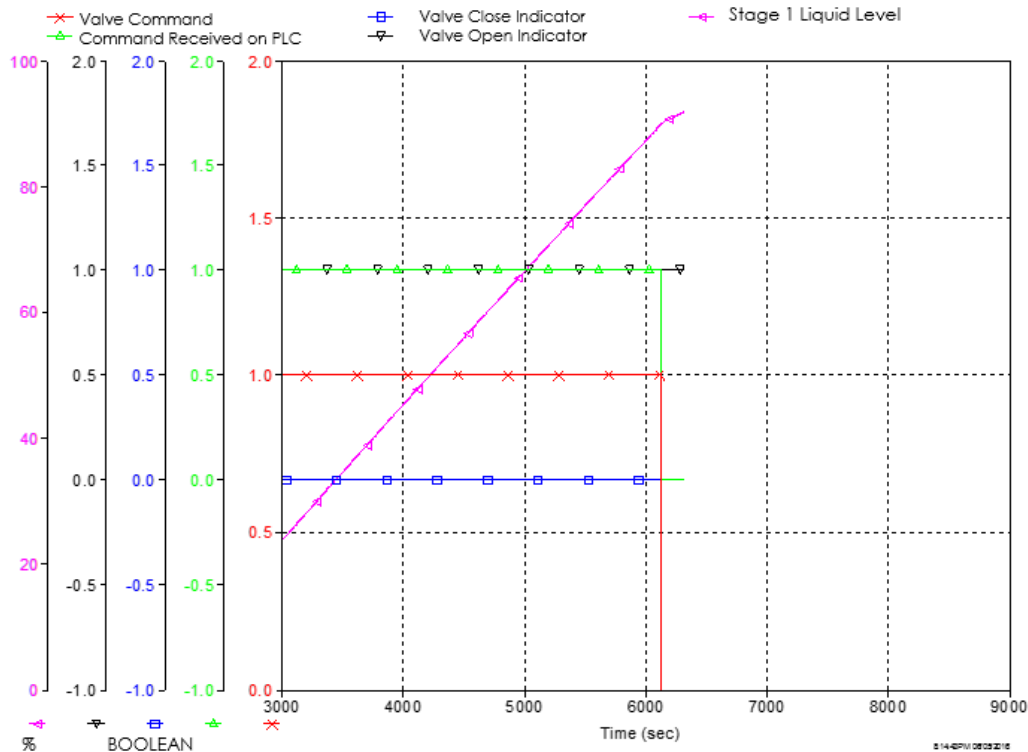
- Mitigation Actions
 - Operator Notification
 - Continue Operations
 - Liquid level keeps increasing



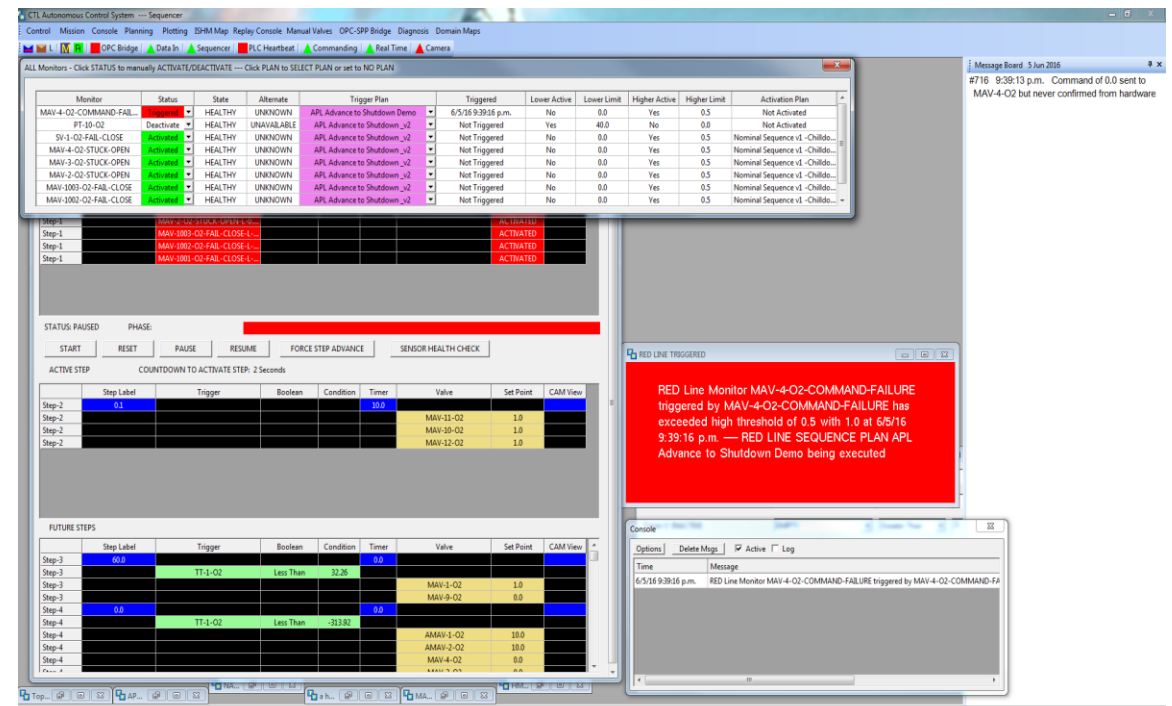
OFF-NOMINAL OPERATIONS

- Safety Critical
 - Valve fails to respond command
 - Overfill operation might occur

Safety Critical Failure: MAV-4-O2 Valve Fails to Respond



- Mitigation Actions
 - Operator Notification
 - Automated abort of nominal plan
 - Executes safing plan

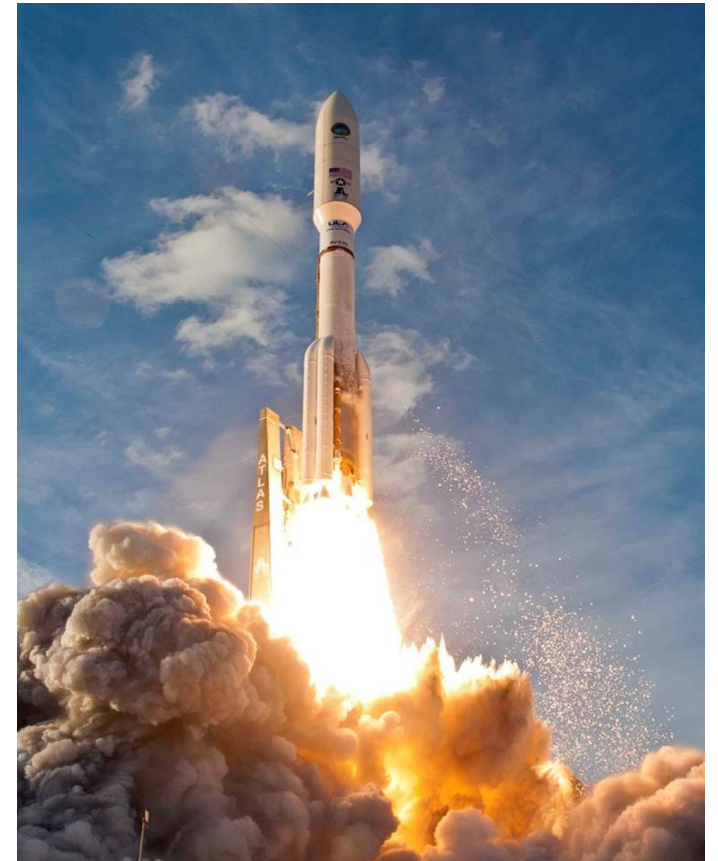


CONCLUSIONS

- AOS: Verification and Validation for Autonomous Operations by using physics models and simulator
- Application development supports real-time ground support equipment (GSE) for cryogenic **propellant** commodity (LO2 and LCH4)
- Support mitigation procedures that allows safe continuation of operations
- NASA Technology Readiness Level (TRL) from validation in laboratory environments (Level 4) to validation in relevant environments (Level 5)

WHAT'S NEXT?

- Increase to higher TRL 5 → 6
- Test in Real Ground Support Equipment (GSE)
- Real cryogenic propellant: LO₂ and LCH₄
- Generalize code to support many applications
- Improve models by redesign and/or modifications
- Unit and Regression Testing
- Pursue Class B Safety Critical Classification
- Meet NASA Safety Standards for and Software Design Processes for Operations (Fielded Use)

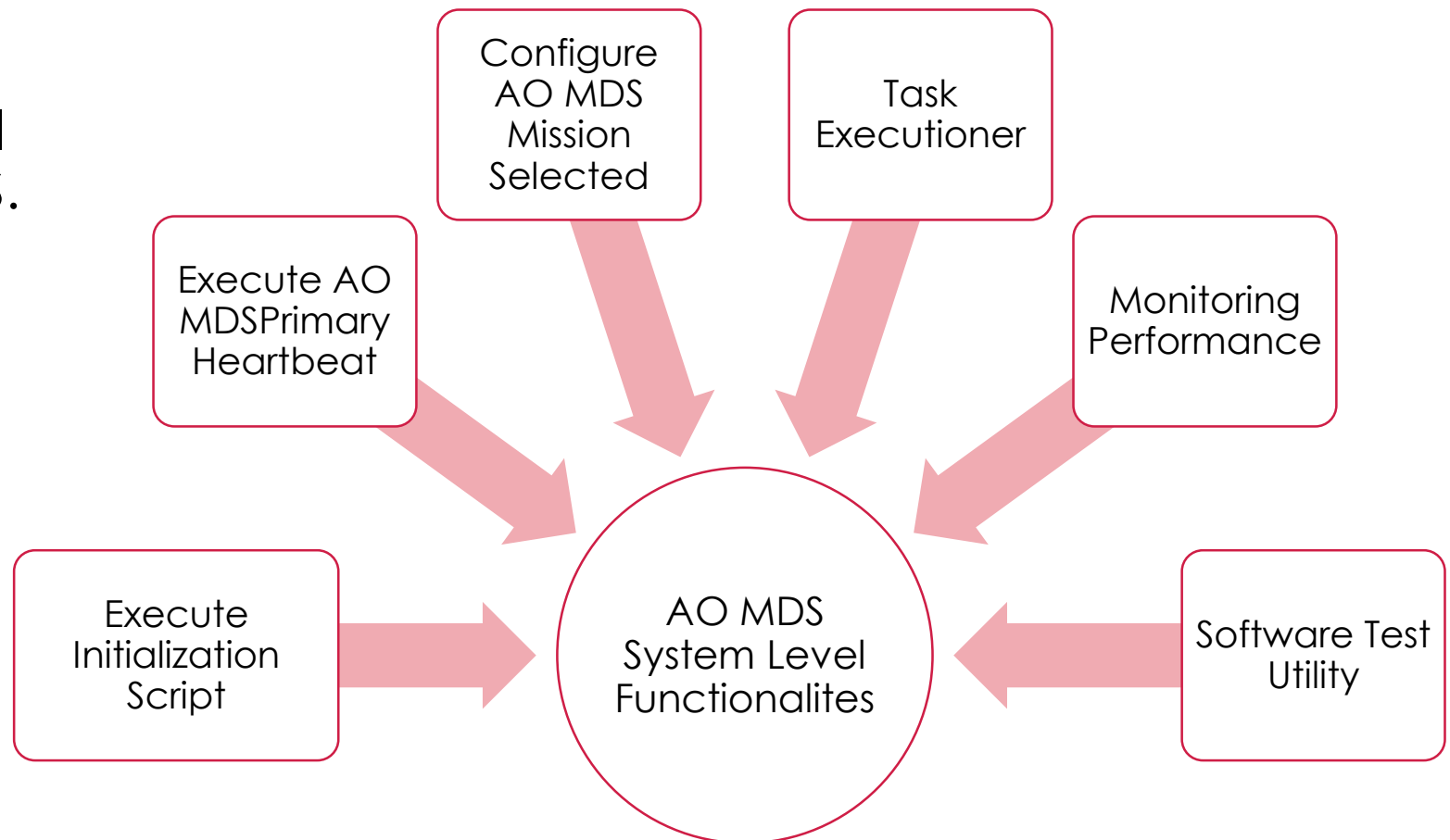


AUTONOMOUS OPERATIONS MISSION DEVELOPMENT SUITE (AO MDS)



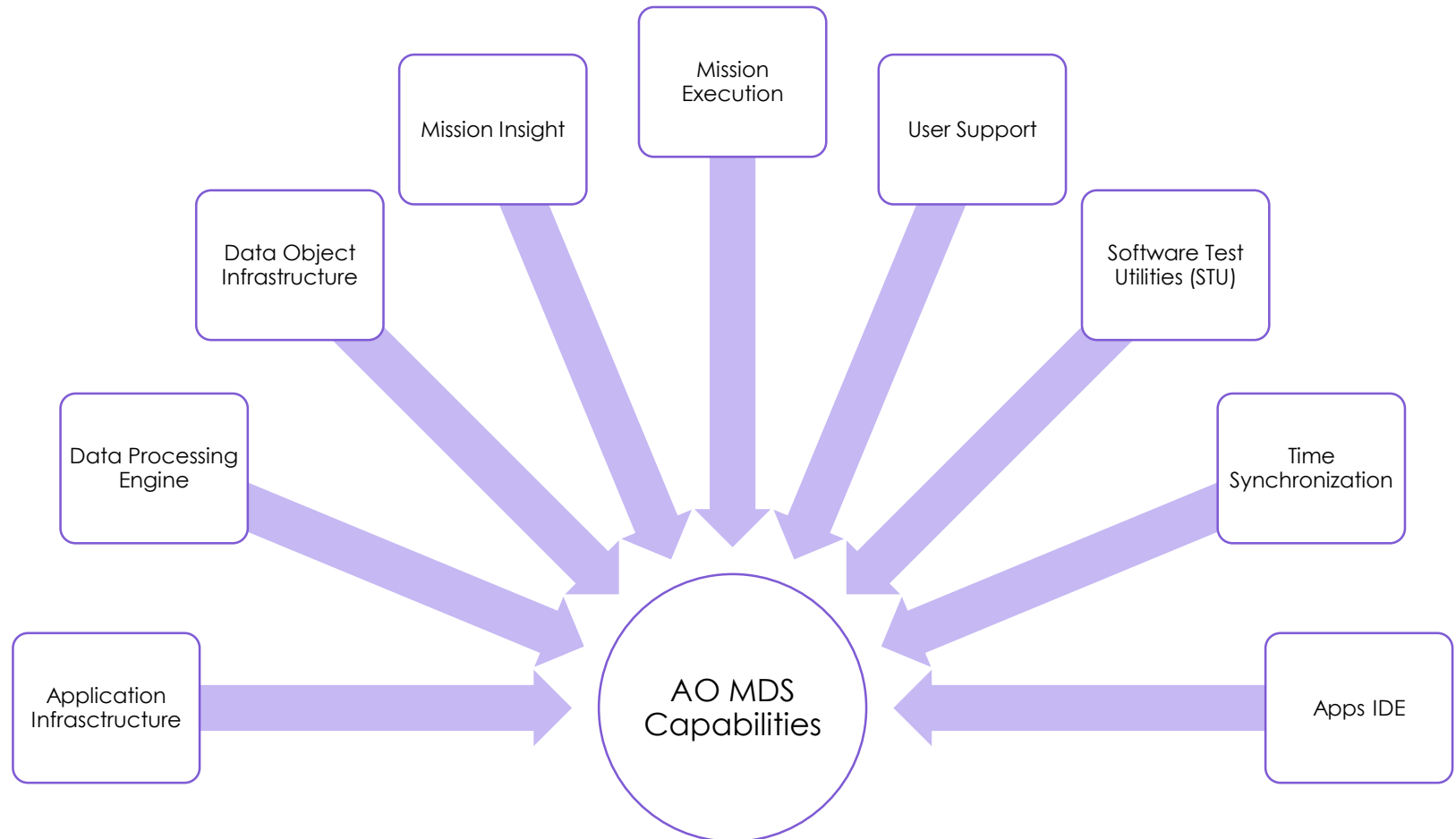
SOFTWARE ARCHITECTURE

- Tier 0: System level functionalities that are fundamental to the overall capabilities of the AO MDS.
- Tier 1: Primary capabilities of the AO MDS.
- Tier 2: Component that correspond to the primary capabilities on the AO MDS.



SOFTWARE ARCHITECTURE

- Application Layer
- I/O Management and Processing
- Mission Plan Management
- Mission Model
- Unit and Regression Testing
- System Synch.
- IDE
- User Interaction



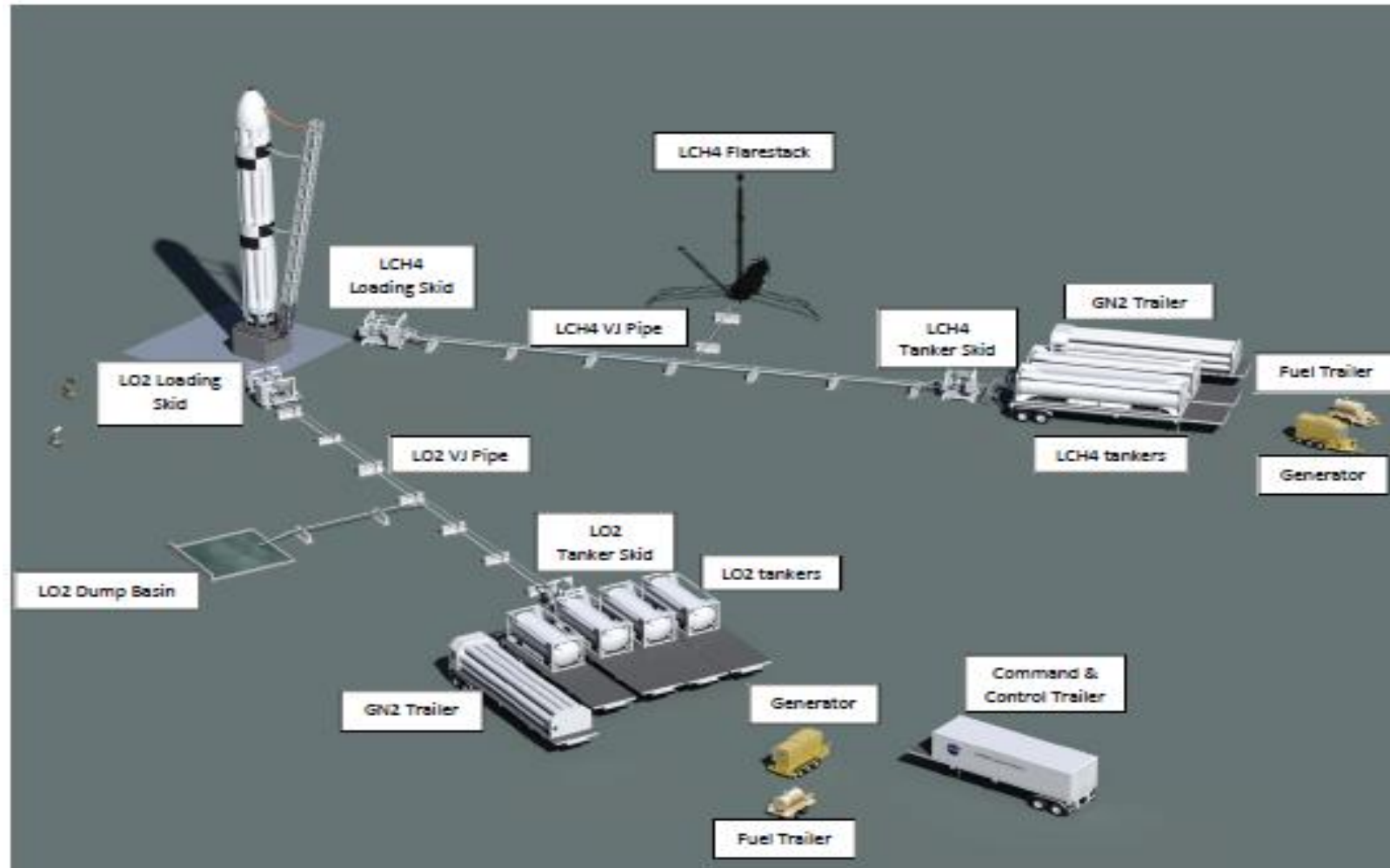
- Included in the AO MDS is the ability to
 - Develop applications using the Integrated Development Environment (IDE)
 - The AO STU provides unit and regression testing of all application and AO MDS
 - Execute Missions Using the AO Run Time Environment (RTE)
 - Development version
 - Deployable version
 - Libraries will grow with each new mission (currently – primarily fluid/cryogenic)

The AO MDS is designed to make application software component development fast and affordable for safety critical applications which is why focus is on NPR 7150.2B compliance

NASA SAFETY, PROCESSES AND STANDARDS

- Acquired and configured the CollabNet TeamForge Application Lifecycle Management (ALM) tool to manage our requirements, project planning, and software configuration management.
- Working toward meeting the NPR 7150.2B Class B Safety Critical compliance.
- Established coding standards for the AO-MDS/G2 development.
- Established project specific desk instructions that align to the KDPs (Key Decision Points - Life Cycle)
- Developed an organizational training plan
- Updated the Software Assurance Plan

APPLICATION – UPSS AND IRON ROCKET



CRYOGENIC PROPELLANT LOADING OPERATIONS

LOX UPSS at Pad B – Up Close View of
ISO Container and Storage Skid



LOX UPSS at Pad B – Up Close View of
Vehicle Skid - 1st, 2nd, 3rd Stage Supply and Drain I/F



LOX UPSS at Pad B – Up Close View of
Vehicle Skid - 1st, 2nd, 3rd Stage Supply and Drain I/F



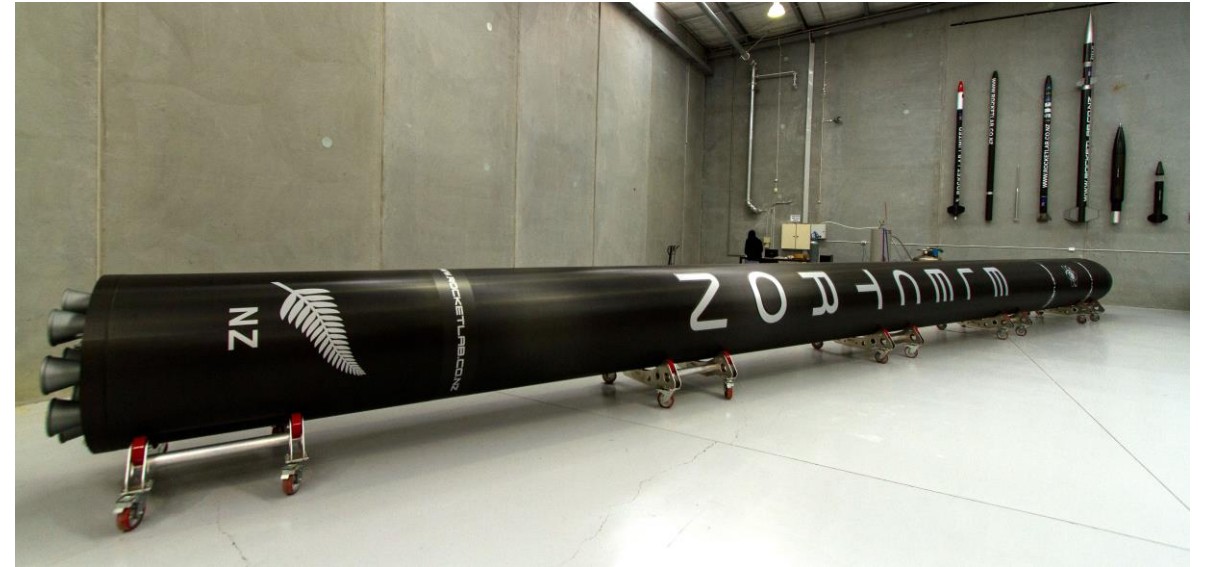
LOX UPSS at Pad B
ISO Container and Storage Skid on Left Hand Side



DTS LOX – Iron Rocket (Vehicle Propellant Tank Simulator)
1st Stage is 3000 gallons, 2nd/3rd Stages are 500 gallons



AIMING FOR SMALL PAYLOAD VEHICLES



AO MDS POTENTIAL



In-Situ Resource Utilization



ORION: On Orbit Operations



Habitation Modules Operations



CONCLUSION

- AO MDS provides generic capability to develop/execute mission specific application software for several space applications
- AO MDS is designed to make application software component development fast and affordable for safety critical applications
- Increase in modeling and testing capabilities
- Follows NASA Processes and certified to be Class B Safety Critical
- Potential to increase TRL Level from 6 (prototype demonstration in relevant environment (ground/space)) to 7 (system prototype demonstration in space environment)



ACKNOWLEDGMENTS

- NASA KSC: John (Jay) Gurecki, Gerald (Jerry) Stahl, Caylyne Shelton, Joanna Johnson, Justin Youney, David Moyer, Robin Hurst, and Kelley Bartlett
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- General Atomics: Kim Wilkins
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- NASA Headquarters: NASA Advanced Exploration Systems under the leadership of Jason Crusan and Richard McGuinnis.

QUESTION AND ANSWERS



BACKUP SLIDES



HEALTH MONITORING

- Nominal
 - Phase Detection
 - Flow Subsystem
- Off-Nominal
 - Leak Detection
 - Valve Consistency



Integrated Functionality
(Includes Task Execution)

Application Infrastructure
(Required to Build Application
Software Components)

Mission Execution
(Includes Creating/Executing
Plans and Redlines)

Mission Insight
(Integrated System
Health Monitoring)

Data Object Infrastructure

Data Processing Engine
(Includes Plot, Log, and Data
Distribution From External Sources)

Application Integrated
Development Environment
(Apps IDE)

User Support